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INFRARED EMISSION FROM THE SUPERNOVA REMNANT PUPPIS A: DUST AND GAS PARAMETERS

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Abstract.

We have modelled the infrared (IR) spectra of collisionally heated dust at several regions across the supernova remnant (SNR) Puppis A. Through the comparision of the actual and model spectra, we are able to narrow the possible range of gas density and temperature within these areas. From the models, we also find information on the minimum and maximum dust grain sizes, and the amount of sputtering which has occurred. Finally, for these regions, we derive the mass of gas and dust, the IR luminosity, the effective thickness, and the length of time since the dust was swept up by the SNR.

I. INTRODUCTION

Puppis A is one of the most prominent supernova remnants in the infrared. The correlation of its IR and X-ray emission is excellent, while the correlations between the IR and radio or optical emission are significantly worse. This leads us to believe that the IR emission is predominantly due to swept-up interstellar dust collisionally heated by the shocked gas within the expanding SNR. We have modelled the IR emission at several regions starting from the gas temperature and density, which are not always known uniquely, and the infrared flux densities. Next, with the selection of a grain size distribution, we determine the infrared spectrum of the dust, collisionally heated by a gas at the applicable density and temperature. We adjust the amount of sputtering and the size limits of the dust distribution to find the model spectrum which best fits the data. From the best models, we derive various physical parameters of the gas and dust at the local regions which are examined.

II. X-RAY AND IR DATA

The gas density and temperature were derived at several 6' diameter regions across Puppis A, through modelling the X-ray spectra obtained with the Einstein satellite's Solid State Spectrometer (SSS) (Szymkowiak 1985). These region are indicated in Figure 1.

The IR flux densities were measured from the Infrared Astronomical Satellite (IRAS) coadded data over the same regions as observed with the SSS. A planar background was subtracted from the entire region of the SNR. For region C an additional background component, with a spectrum matching that of the cloud immediately to the east, was subtracted from the observed flux densities before modelling.

III. MODELLING THE IR EMISSION

To model the observed IR emission, we used a mixture of graphite and silicate grains with a number density in the a to $a+da$ size interval given by:

$$\text{where } n_{\text{dust}}(a) da = n_0 f(a) da, \\ f(a) \sim a^{-k}, \quad \text{for } a_{\min} < a < a_{\max},$$

normalized so that $\int f(a) da = 1$,

and

$$n_0(\text{graphite}) = Z_g C_g n_{\text{gas}} \\ n_0(\text{silicate}) = Z_s C_s n_{\text{gas}},$$

where n_{gas} is the number density of the gas, C_g and C_s are constants which depend on the index (k), and the limits (a_{\min} and a_{\max}) of the power law distribution, and Z_g and Z_s are the dust to gas mass ratios of graphite and silicate, taken to be $Z_g = 0.0040$ and $Z_s = 0.0035$ throughout this work.

Two of the models used were an MRN distribution (Mathis, Rumpl, and Nordsieck 1977) extended to smaller grain sizes (EMRN), and an extended MRN distribution with larger grain sizes also included (EMRNL). The power law indicies of both of these distributions are $k = -3.5$. The lower limits for both distributions were a_{\min} (graphite) = $0.0003\mu\text{m}$, a_{\min} (silicate) = $0.0026\mu\text{m}$, and the upper limits for the EMRN distribution were a_{\max} (graphite), a_{\max} (silicate) = $0.25\mu\text{m}$, while for the EMRNL distribution the upper limits were a_{\max} (graphite), a_{\max} (silicate) = $1.0\mu\text{m}$.

The fluxes from the dust models were calculated according to:

$$F(\lambda) = \sum_{\text{comp.}} \int_{a_{\min}}^{a_{\max}} n_{\text{dust}}(a) \left[\int_{T_{\text{eq}}}^{T_{\text{avap}}} P(a, T_d) B_\lambda(T_d) Q_\lambda(a) dT_d \right] da.$$

The sum is over grain compositions. The function $P(a, T_d)$ is the temperature probability distribution of dust grains of size a . This function depends upon the density and temperature of the gas which is heating the dust. Under the conditions found within Puppis A, for grain sizes larger than $\sim 0.02\mu\text{m}$ the effects of stochastic heating become less important and these grains are found within a narrow range of their equilibrium temperatures ($T_{\text{eq}}(a)$). Thus, for these larger grains we made the approximation: $P(a, T_d) = \delta(T_d - T_{\text{eq}}(a))$.

A decrease in grain size due to sputtering, $\Delta a(\text{sput.})$, was simulated by using a size distribution based on the initial distribution described above: $n_{\text{sput.}}(a) \sim f(a + \Delta a(\text{sput.}))$. This sputtered grain size distribution was then used in the integral defining the flux.

For each region we created several model spectra. In most cases the EMRN dust model provided a reasonably good spectrum. Models using different amounts of sputtering and size limits were created to find better fits to the observed data, and to determine what range of variation of the dust model parameters was allowable.

IV. RESULTS

The amount of sputtering that has taken place in a region can be related to the length time (τ) for which the gas has been subjected to sputtering by: $\Delta a(\text{sput.}) = 0.005 n_{\text{gas}} \tau$, where $\Delta a(\text{sput.})$ is in \AA , n_{gas} is in cm^{-3} , and τ is in years (Draine and Salpeter 1979). The normalization factors needed to match the model spectra to the observed spectra are directly related to the current mass of dust in the given regions. The depletion of the dust

due to sputtering is defined as the ratio of the current dust mass to the initial dust mass before sputtering had acted to erode the grains. The mass of gas in the region is found from the initial dust mass and the dust to gas mass ratio. The mass of gas and the gas density are then used to derive the effective thickness of each region. (The width of each region examined is $1.75d$ pc, where d is the distance to Puppis A in kpc.) The IR luminosity is found from the integral of the spectrum over wavelength.

For each of the regions, Table 1 lists the input parameters used in calculating the model spectra, the dust model that provides the best fitting model spectrum, and various physical parameters which can be derived from the models.

TABLE 1

	Region	C	I1	I2	I3	N	R
Input Parameters	IR flux densities(Jy)						
	12 μm	1.22	<1.56	<1.56	<1.56	<1.56	<1.56
	25 μm	14.8	13.1	10.2	7.2	7.7	2.0
	60 μm	63.2	50.7	44.7	33.7	37.9	8.9
	100 μm	36.3	44.6	31.7	16.9	19.2	19.7
	Gas density (cm^{-3})	4.0	1.3	1.3	1.3	1.3	1.3
	Gas temperature (10^6 K)	3.2	5.6	5.6	5.6	10.	3.2
Best Fitting Size	Dust Model distribution	EMRN	EMRN	EMRN	EMRN	EMRN	EMRNL
Derived Parameters	Model flux densities(Jy)						
	12 μm	1.6	1.2	1.0	0.8	0.6	0.3
	25 μm	14.7	10.8	9.09	6.68	7.02	1.94
	60 μm	63.3	55.4	46.8	34.4	38.9	9.7
	100 μm	34.9	34.8	29.4	21.6	21.5	8.38
	$\Delta a(\text{sput.})$ (\AA)	6	0.0	0.0	0.0	0.0	0.0
	Sputtering age (yrs)	~300	<460	<460	<460	<460	<460
	Depletion	0.906	1.0	1.0	1.0	1.0	1.0
	Dust mass ($10^{-3} M_{\odot}/\text{kpc}^2$)	1.59	2.13	1.80	1.32	0.96	1.27
	Gas mass (M_{\odot}/kpc^2)	0.234	0.284	0.240	0.176	0.128	0.169
	Effective thickness(pc)	0.77	1.9	2.4	1.8	1.3	1.7
	IR Luminosity (L_{\odot}/kpc^2)	174	148	125	91.5	98.2	28.0

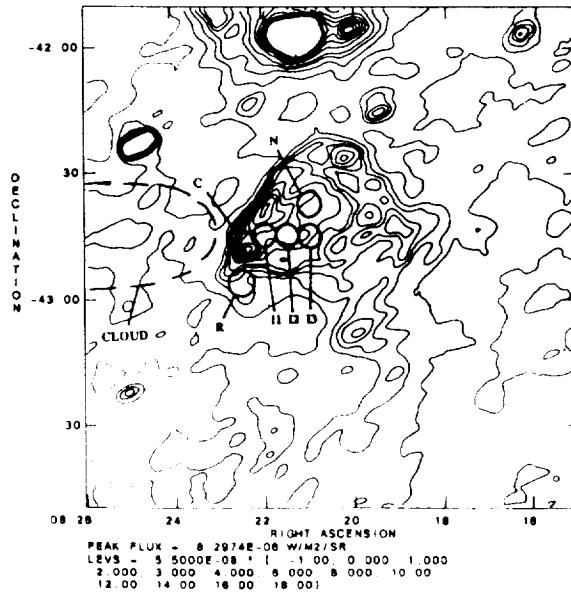


Figure 1: Puppis A at $60\mu\text{m}$

The diamond shaped object, roughly 50' across, at the center of Figure 1 is the SNR Puppis A as seen by the IRAS at $60\mu\text{m}$. The circles indicate the regions observed with the Einstein SSS and analyzed by Szymkowiak (1985). To the east of Puppis A lies a cloud, visible in the IR as well as through HI and CO observations (Dubner and Arnal 1988), which is interacting with the SNR.

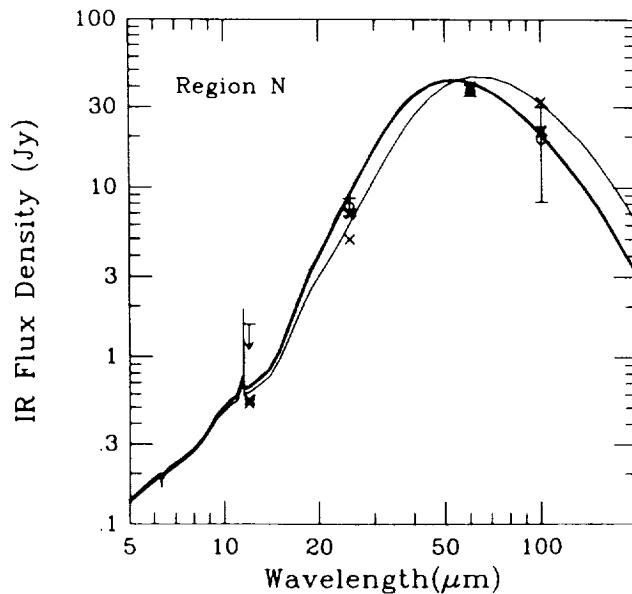


Figure 2: IR as a Diagnostic of Plasma Parameters

For region N, two different sets of gas density and temperature can be used to produce equally good models of the X-ray spectrum. However, only one of these sets leads to a good model of the IR spectrum. (heavy line : $n = 1.3 \text{ cm}^{-3}$, $T = 10^7 \text{ K}$; light line: $n = 0.4 \text{ cm}^{-3}$, $T = 10^7 \text{ K}$)

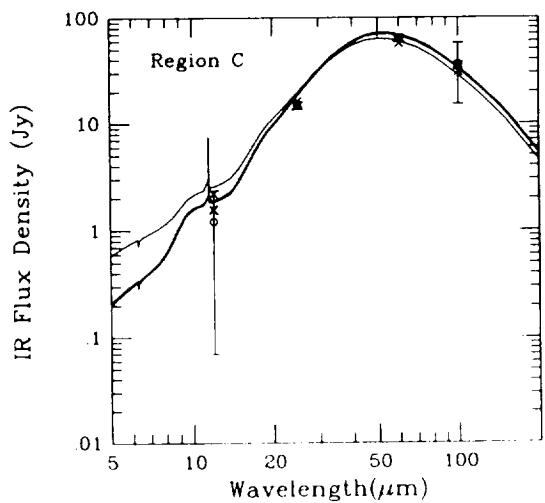


Figure 3: The Effects of Sputtering

For region C, the IR spectrum modelled from the extended MRN grain size distribution is too high at $25\mu\text{m}$ and too low at $60\mu\text{m}$ (light line). An improved spectrum results when grains with the same initial size distribution are sputtered so that all grains are decreased in size by 6\AA (heavy line).

Other regions show little or no evidence of sputtering, but are modelled by a less dense gas and therefore a correspondingly lower sputtering rate.

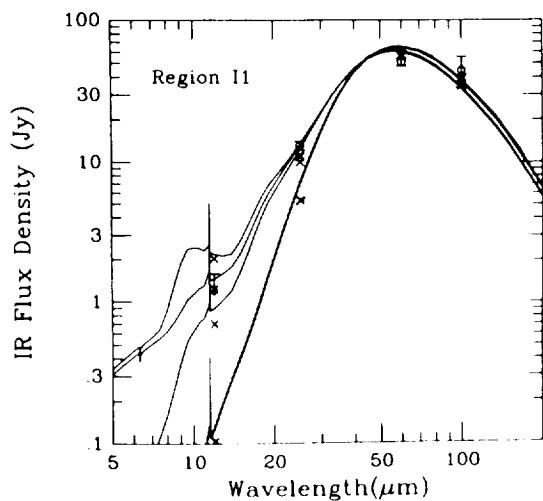


Figure 4: The Effects of Small Grains

Models of the IR spectrum based on a standard MRN size distribution underestimate the $25\mu\text{m}$ flux densities of all regions (heavy line). Extending the MRN spectrum to smaller grain sizes leads to better model IR spectra (light lines, from higher to lower: $a_{\min}(\text{graphite})$, $a_{\min}(\text{silicate}) = 3\text{\AA}$; $a_{\min}(\text{graphite}) = 3\text{\AA}$, $a_{\min}(\text{silicate}) = 26\text{\AA}$; $a_{\min}(\text{graphite})$, $a_{\min}(\text{silicate}) = 26\text{\AA}$). The $12\mu\text{m}$ flux density is most strongly affected by the lower limit of the grain size distribution. Unfortunately, only in region C is there any detectable IR emission.

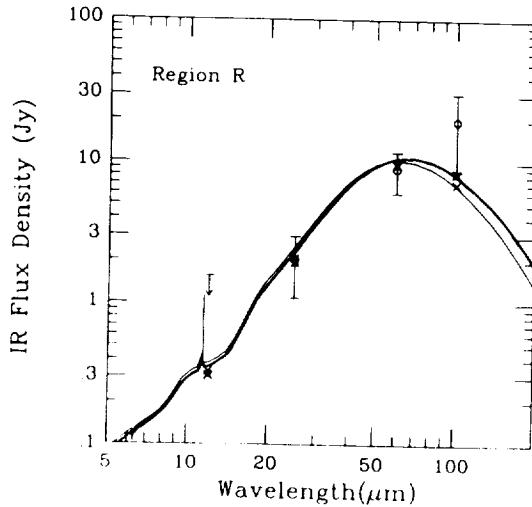


Figure 5: The Effects of Large Grains

Region R shows an observed $100\mu\text{m}$ flux density which is underestimated by the emission modelled from an extended MRN distribution of grain sizes (light line). Increasing the upper limit of the grain size distribution from $0.25\mu\text{m}$ to $1.0\mu\text{m}$ yields a spectrum with an improved fit (heavy line).

However, improved results can also be obtained by subtracting an additional background component with the same spectrum as the cloud immediately to the east of this region.

V. CONCLUSION

Through this examination of selected regions of the SNR Puppis A, we have been able to show that: 1) the gas densities and temperatures derived from analysis of the X-ray spectra lead to good models of the IR spectra of collisionally heated dust, which provide estimates of the masses, luminosities, ages, and effective thicknesses of these regions (see Table 1), 2) the model IR spectra can be used to determine the best choice of gas density and temperature in cases where more than one combination can be used to model the X-ray spectra, 3) the standard MRN grain size distribution must be extended to smaller sizes, which are stochastically heated, to achieve the best fitting model IR spectra, 4) the limits set on the amount of sputtering which has occurred, indicate that most of the dust has resided in the hot plasma of the SNR for <450 years, and 5) the results for regions R and C indicate either the superposition of the SNR and a nearby cloud, or the presence of additional large dust grains.

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